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Bench-top Lubricity Evaluator Correlation with Military Rotary Fuel Injection Pump Test Rig

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ABSTRACT

U.S. military vehicles and equipment can be exposed to poor lubricity fuels. Lubricity-improving additives (LIA) are utilized to remedy fuel lubricity to satisfactory levels. The military is interested in developing an affordable and fast bench-top lubricity evaluator capable of measuring fuel lubricity and improvements provided by LIA in order to replace the expensive and time consuming Military Rotary Fuel Injection Pump Test Rig. Previous tests have shown that certain bench-top lubricity evaluators are sensitive to LIA and correlate well with the pump test rig but lack precision. In an effort to improve the viability of bench-top evaluators for measuring fluid lubricity, a parameter study was conducted to determine if modifications to the bench-top lubricity methodology, apparatus, and operating conditions would improve the sensitivity and precision. Data from the study suggests that improved precision can be achieved by ensuring uniform contact between test surfaces (ball and disks), and improved sensitivity by increasing test fluid temperature to 40°C or 50°C. Implementing these modifications to the bench-top lubricity evaluator will increase the differentiation between a “poor” and “good” lubricity fluid.

INTRODUCTION

The U.S. Military adopted a Single Fuel Forward (or Single Fuel in the Battlefield) policy to decrease the logistical burdens associated with supplying and transporting multiple fuels to the battlefield. The policy states that all military tactical vehicles and equipment must be capable of utilizing JP-8 or JP-5 as the primary fuel [1]. JP-8 and JP-5 are simply Jet A/Jet A-1 blended with three additives: Corrosion Inhibitor/Lubricity Improving (CI/LI), Static Dissipater Additive (SDA), and Fuel System Icing Inhibitor (FSII) as specified in MIL-PRF-83133 and MIL-DTL-5624 (JP-5 has a greater flash point then JP-8) [2,3]. CI/LI provides corrosion resistance and lubrication to fuel-wetted components. As a result, Jet A/Jet A-1, a known poor lubricity fuel, additized with CI/LI improves fuel lubrication to satisfactory levels for acceptable use in military equipment. Without the lubricity improvement, fuel injection pump components develop wear more rapidly resulting in degenerative pump performance and wear-induced pump failure. The military conducted tests to confirm that CI/LI is effective at improving Jet A/Jet A-1 lubricity to satisfactory levels when blended at the minimum and maximum effective concentrations (between 9 and 22.5 mg/L, as specified by QPL-25017) using the Military Rotary Fuel Injection Pump Test Rig [4,5]. The test rig is the most reliable procedure to detect fluid lubricity and lubricity improvement provided by additives. The test rig and procedure are similar to an ASTM D 6898 standard test method for “Evaluating Diesel Fuel Lubricity by an Injection Pump Test Rig”, but customized to evaluate military rotary fuel injection pumps found in the High Mobility Multi-Wheeled Vehicle (HMMWV) [6]. Although accurate and shown to be representative of field operation, the rig is very expensive to operate and time consuming. As a result, the military is interested in developing an affordable bench-top lubricity evaluator capable of accurately measuring fluid lubricity and assessing lubricity improvement provided by additives. Although the scope of this research focuses on jet fuel, a sensitive and precise bench-top lubricity evaluator would have application with diesel fuel lubricity. The following report describes the evaluation of a bench-top lubricity evaluator to correlate with the Military Rotary Fuel Injection Pump Test Rig.

BACKGROUND

The most common bench-top lubricity test methods are Ball-On-Cylinder Lubricity Evaluator (BOCLE), Scuffing Load Ball-On-Cylinder Lubricity Evaluator (SLBOCLE),

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High-Frequency Reciprocating Rig (HFRR at 60°C), and the Ball on Three Disks (BOTD). Previous reports have shown the SLBOCLE and HFRR are not sensitive to CI/LI additive and cannot predict lubricity improvement effectively provided by the additive as determined in Military Rotary Fuel Injection Pump Test Rig evaluations. In contrast, the BOCLE and BOTD have a directional correlation revealing reductions in wear scar diameter with increasing effective concentration of CI/LI [6,7,8,9].

BENCH-TOP LUBRICITY EVALUATOR CORRELATION

Neat S-5, an unadditized synthetic Fischer-Tropsch fuel meeting the properties listed in Table I of the JP-5 specification (MIL-DTL-5624), with the exception of density, and S-5 additized with CI/LI at the minimum and maximum effective concentrations were evaluated using the Military Rotary Fuel Injection Pump Test Rig and four bench-top lubricity evaluators: BOCLE, SLBOCLE, HFRR, and BOTD [6]. Fuel injection pumps operating on neat S-5 functioned for duration of 96.5 and 150.7 hours, for pump test one and two respectively, until the pumps failed from wear induced failure. S-5 additized with minimum (12 mg/L) and maximum (22.5 mg/L) concentrations of CI/LI were operated for 500 hours without failure; these pumps were inspected and showed no abnormal wear. Table 1 summarizes the results of the fuel injection pump tests. The BOCLE, SLBOCLE, and HFRR (60°C) tests were conducted according to their ASTM procedures D5001, D6078, and D6079 respectively. BOTD tests were conducted according to an ASTM working group proposed test methodology (P-TM) developed in 2000 [10]. The BOTD P-TM will be discussed in a later section. For each bench-top lubricity evaluator, a minimum of three runs were conducted for each sample and used to calculate an average data point. Table 2 summarizes some of the distinguishing test conditions between selected bench-top fuel lubricity evaluator's test methodologies. Figure 1 displays the results of the bench-top lubricity evaluator tests. The SLBOCLE and HFRR did not show lubricity improvement as the concentration of CI/LI was increased. In contrast, the BOCLE and BOTD showed a reduction in wear scar diameters (WSD) as the concentration of CI/LI increased.

Table 1. Summary of Results for Military Rotary Fuel Injection Pump Test Rig [6]

Sample	Test Hours for Pump 1, Pump 2
Neat S-5	96.5, 150.7
S-5 +12 mg/L CI/LI (min effective conc.)	500, 500
S-5 +22.5 mg/L CI/LI (max effective conc.)	500, 500

Table 2. Bench-top Lubricity Evaluator Test Conditions

Test Method	ASTM Test Method	Fluid Temp (°C)	RH (%)	Load (g)	Sample Volume (ml)
BOTD	Proposed (2000) [10]	24	45	2500	35
BOCLE	D5001	25	10	1000	25
SLBOCLE	D6078	25	50	500 to 5000	25
HFRR	D6079	60	>30	200	2

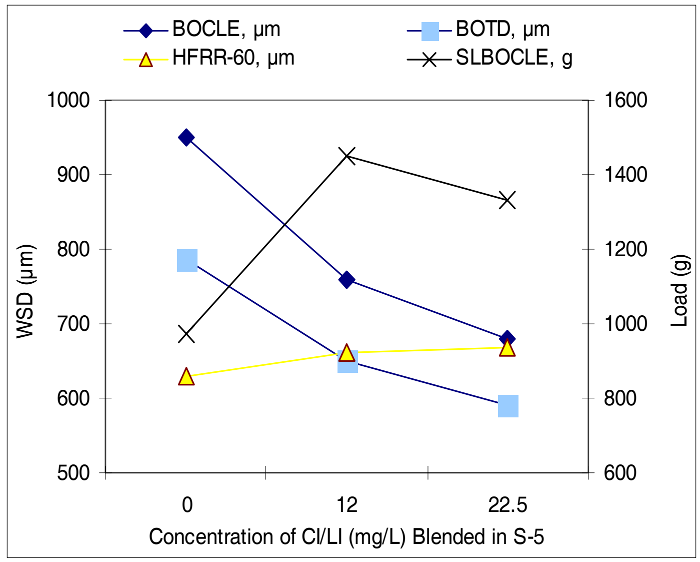

Figure 1. Bench-top Lubricity Evaluator Correlation Data

PROPOSED BOTD TEST METHODOLOGY

The BOTD data displayed in Figure 1 was collected using an ASTM working group P-TM developed in 2000 [10]. The BOTD was used to establish baseline lubricity measurements, namely WSD, for five samples:

1. ASTM Fluid A: Good lubricity fluid
2. ASTM Fluid B: Poor lubricity fluid
3. Neat S-5
4. S-5 with 12 mg/L of CI/LI MIL-PRF-25017
5. S-5 with 22.5 mg/L of CI/LI MIL-PRF-25017

ASTM Fluid A and B are ASTM reference samples with known lubricity [7].

The BOTD test results using the ASTM working group P-TM are summarized in greater detail in Table 3. This data suggests unadditized S-5 has worse lubricity than ASTM Fluid B, which is a known poor lubricity fuel. As the concentration of CI/LI additive blended with S-5 is increased, the resulting WSD decreases in a non-linear fashion. The relationship between additive concentration

and wear development predicted by the BOTD correlates well with the Military Rotary Fuel Injection Pump Test Rig. Thus, the BOTD P-TM is considered sensitive to CI/LI and can accurately predict lubricity improvement provided by the concentration of additive. However, BOTD P-TM data contains large standard deviations in average WSD indicating the need to improve precision of the test method. Additional improvements in BOTD P-TM sensitivity may be achieved by increasing the differentiation in WSD between poor lubricity fluids (i.e. neat S-5) and good lubricity fluids (i.e. S-5 treated with CI/LI). Thus, a study was conducted to evaluate various parameters affecting test methodology precision and sensitivity. These parameters included:

- Disk surface finish
- Ball material
- Relative Humidity
- Fluid temperature

Table 3. Summary of Results for BOTD P-TM

Sample	Avg. WSD (μm)	Std. Dev. of Avg. WSD
S-5 (Baseline)	785	40
S5+12.0 mg/L CI/LI	649	83
S5+22.5 mg/L CI/LI	590	33
ASTM Fluid A	387	34
ASTM Fluid B	610	67

IMPROVED MODIFIED METHODOLOGY

The BOTD was used to evaluate the five fluid samples listed in Table 3. The data generated under the proposed BOTD test methodology (summarized in Table 3) was used as the baseline lubricity measurement. Subsequently, the P-TM was modified to determine the affect of various test conditions on the sensitivity and precision of the methodology. The entire BOTD test data developed for this report is provided in Appendix Table A-1.

Many of the BOTD test method parameter modifications selected for this study are standard procedure for other bench-top lubricity evaluators.

SURFACE FINISHING / BALL MATERIAL

The proposed BOTD test methodology was modified to include a surface finishing technique for the three specimen disks. According to the P-TM, the specimen disks were composed of Steel 4130 (31-33 R_c) and had a surface finish of five to eight micro-inch R_a [11]. Although the methodology specified a surface finish, often the specimen disks did not visually appear to be consistent. To reduce any inconsistencies, a surface finishing technique was implemented. The specimen disks were polished using a 600-μm and subsequently 30-μm grit silicon carbide abrasive sheets. Finally, the specimen disks were polished with a 15-μm grit aluminum oxide polishing powder. After the polishing procedure was completed, all five samples were run using the P-TM modified with the polished specimen disks. The polished specimen disks did not change the contact orientation between the ball and disk.

The P-TM utilizes a ceramic ball composed of aluminum oxide (grade C-25) to impact the three specimen disks. In a modified test methodology, a chrome alloy steel ball made from AISI standard steel No. E-52100 (64-66 R_c), used in the BOCLE and SLBOCLE, was used to impact a second set of polished specimen disks. Again, all five samples were run using the proposed BOTD test methodology modified with the polished specimen disks and steel ball.

ADDITION OF A THERMOCOUPLE

In order to monitor test fluid temperature, a thermocouple was added to the BOTD instrument. The thermocouple was tested in three positions to determine the best positioning that least affects the test's repeatability. The following is a description of the thermocouple position:

1. Thermocouple placed on top of the specimen disks holder.
2. Thermocouple placed on top of the specimen disks holder and sample cup surrounded with a heating tape.
3. A small groove was made in a specimen disks holder. Thermocouple was placed in the groove and on top of the disc holder and the sample cup surrounded by heating tape.

The P-TM, modified with each of the thermocouple placements, was run using S-5.

RELATIVE HUMIDITY

Relative Humidity (RH) is measured in bench-top lubricity evaluators to monitor the affect of moisture on wear development. Variations in RH can result in significant changes to WSD and, consequently, affect precision. Humidity correction factor (HCF) is used by the HFRR to correct and interpolate WSD for a RH value [12,13]. To determine the affects of moisture on wear development, RH was modified from the proposed BOTD test methodology RH of 45% to 10%. All other P-TM conditions were unchanged. S-5, S-5 + 22.5 mg/L of CI/LI, and Fluid A were tested at the lowered humidity.

TEST FLUID TEMPERATURE

Test fluid temperature was modified from the BOTD P-TM temperature of 24°C to three higher temperatures: 40°C, 50°C, and 60°C. Heating tape and Rheostat were

used to heat and control the test fluid temperature to the desired test temperature. A thermocouple placed in a specimen disks holder groove and sample cup surrounded by heating tape was used to monitor and control fluid temperature. All five samples were evaluated at each modified temperature. All other P-TM conditions were unchanged.

RESULTS AND DISCUSSION

The proposed BOTD test methodology was effective at discerning between extremely poor and good lubricity fluids. Furthermore, the methodology was capable of measuring lubricity improvement provided by CI/LI at both minimum and maximum effective concentrations. However, the methodology produced high standard deviations in WSD. Large deviations would make it difficult to classify an unknown fluid's lubricity as poor, mid-range, or good on a single run since the deviation could increase or decrease the WSD into a different lubricity classification.

An aspect considered the most critical aspect for improving the BOTD precision, as noted by the technician performing all test runs, was to ensure proper and uniform contact between the ball and three specimen disks during initial placement at the start of the test. Any instance of improper contact typically resulted in large deviations in WSD per specimen disk. Thus, emphasis must be placed on proper alignment of disks and ball. Although considered a critical aspect, our project did not validate this thru experimentation. It is recommended that a better placement procedure and/or hardware changes be incorporated in the test methodology/hardware.

Implementing a surface finishing procedure to eliminate inconsistencies between specimen disks had modest affects on precision. Combining surface finishing techniques and a steel ball further improved precision. Overshadowing the improved precision in each modification was the loss of sensitivity. Both modifications seemed to reduce the ability to discriminate between poor lubricity (neat) S-5 and additized S-5 with improved lubricity. As shown in Figure 2, the change in WSD between poor lubricity (0 mg/L of additive) and good lubricity (22.5 mg/L of additive) is significantly reduced with the implemented modifications. As a result, the modifications make it more difficult to classify an unknown fluid's lubricity.

The RH was modified from the P-TM of 45% to a lower value of 10%. Varying RH had no affect on WSD precision or sensitivity. According to the data (Appendix Table A-1), this change in moisture had no significant impact on the development of wear in the BOTD bench-top lubricity evaluator.

Test fluid temperature was modified from the P-TM condition of 24°C to three higher temperatures: 40°C, 50°C, and 60°C. Before the fluid temperature was raised, a thermocouple was instrumented to the BOTD. Initial attempts to position the thermocouple atop the specimen disk holder resulted in large standard deviations. Presumably, the thermocouple caused a misalignment between the ball and disks by impinging on the rotating ball holder. As a result, the specimen disk holder was machined with a groove for the thermocouple to lie in. Tests using the thermocouple and groove with heating tape showed improved precision. All high temperature tests were conducted using the machined specimen disk holder.

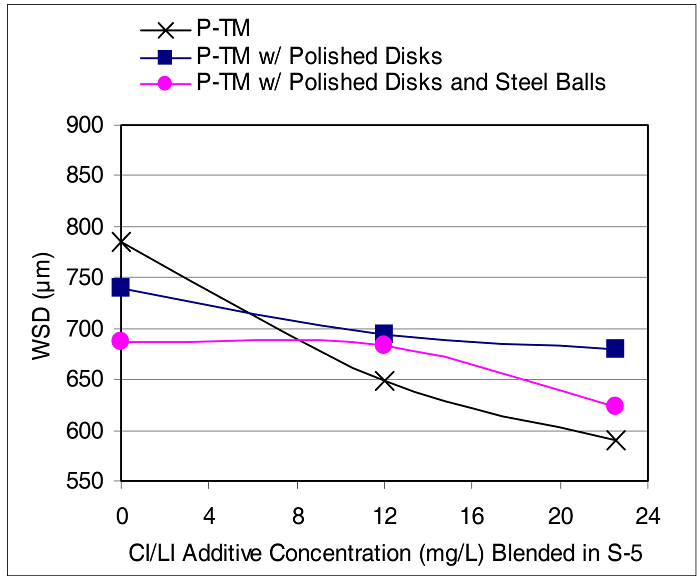

Figure 2. Surface Finishing & Ball Material Modifications (P-TM = Proposed Test Methodology)

The results of test fluid temperature modification on neat and additized S-5 and ASTM Fluid A and B are summarized in Figures 3 and 4 respectively. For poor lubricity fluids, neat S-5 and ASTM Fluid B, WSD tends to increase with increased test fluid temperature. For neat S-5, increasing the test fluid temperature to 40°C and 50°C increased the WSD above the baseline result at 24°C (P-TM fluid temperature); belying this trend, however, is that relatively no change in WSD was seen at 60°C. This run should be repeated as a high standard deviation was experienced. For ASTM Fluid B, increasing the test fluid temperature to 50°C and 60°C increased the WSD above the baseline WSD developed at 24°C; a smaller change in WSD is seen at 40°C and the change is within the standard deviation for the WSD developed at 24°C. For good lubricity fluids, S-5 blended with 12 mg/L and 22.5 CI/LI, and ASTM Fluid A, WSD is not significantly affected by temperature as statistically similar WSD are produced at all four test temperatures.

In general, increasing test fluid temperature seems to increase WSD for poor lubricity fluids and have no affect on WSD for good lubricity fluids. This statement is especially true for 50°C test data. By increasing test fluid temperature to 50°C, the severity of the test has increased. Hence, disks lubricated with poor lubricity fluids will develop more wear, while disks lubricated with

good lubricity fluids will be protected and develop minimal wear. By increasing the differentiation in WSD for poor and good lubricity fluids, it will be easier to classify the lubricity of an unknown fluid.

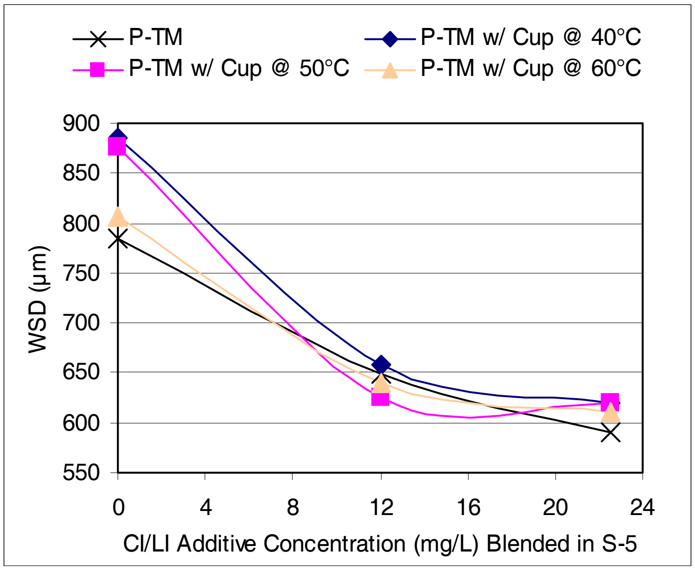

Figure 3. Fluid Temperature Modifications, S-5

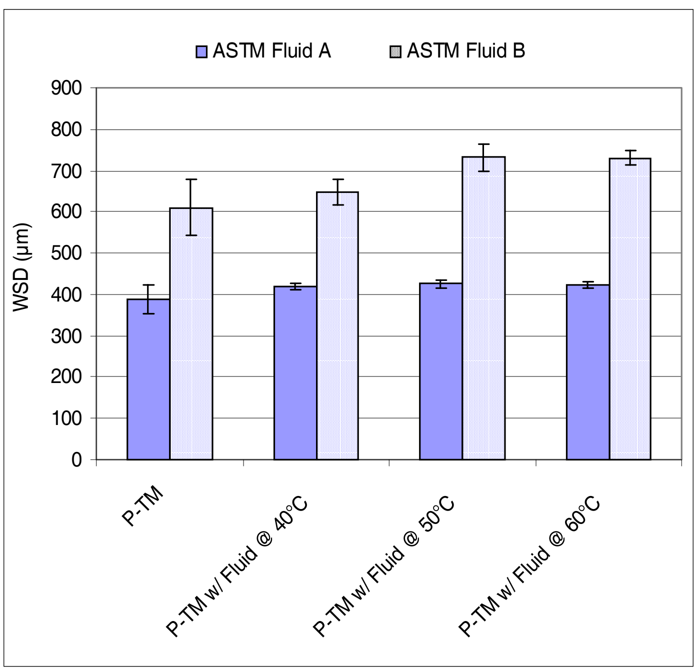

Figure 4. ASTM Fluid A & B – Test Result Summary

CONCLUSION AND RECOMMENDATIONS

The BOTD bench-top lubricity evaluator tested is capable of measuring fluid lubricity and lubricity improvement provided by CI/LI. Improvements to the test methodology and instrumentation will improve the precision and sensitivity of the instrument to better correlate with the Military Rotary Fuel Injection Pump Test Rig. According to the data collected, the following conclusions can be made regarding the bench-top lubricity evaluator:

1. Proper alignment and uniform contact between the ball and three specimen disks is considered the most critical aspect for obtaining high precision data and the hardware needs to be modified to ensure proper alignment.

2. Increasing test fluid temperature appears to increase WSD for poor lubricity fluids and have no affect on WSD for good lubricity fluids. More data should be populated to confirm this relationship.

3. Increasing test fluid temperature to 50°C increases the differentiation between a "good" and "poor" lubricity fluid.

4. When measuring fluid temperature, a thermocouple should be incorporated into the instrument seamlessly (via a groove) so as to not interfere with the alignment of the ball and disks.

5. The surface finishing techniques implemented in this study and use of a steel ball appears to decrease test sensitivity differentiation between "good' and "poor" lubricity fluid.

6. Relative humidity does not appear to have an affect on WSD, test sensitivity, or precision under the conditions investigated.

It is recommended that load be included in further evaluation of BOTD methodology to improve precision and lubricity additive sensitivity.

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APPENDIX

Table A-1. Summary of BOTD Testing										
	S-5		**S5+12.0 mg/L Cl**		**S5+22.5 mg/L Cl**		**ASTM Fluid A**		**ASTM Fluid B**	
Test Procedure and/or Modification	Avg. WSD (μm)	Std. Dev of Avg. WSD	Avg. WSD (μm)	Std. Dev. of Avg. WSD	Avg. WSD (μm)	Std Dev of Avg. WSD	Avg. WSD (μm)	Std. Dev. of Avg. WSD	Avg. WSD (μm)	Std. Dev. of Avg. WSD
P-TM	785	40	649	83	590	33	387	34	610*	67*
P-TM w/ Polished Disks	739	21	694	39	680	42	371	71	623	20
P-TM w/ Polished Disks and Steel Balls	687	15	683	32	623	3	316	2	599	11
P-TM w/ Thermocouple (No Groove)	740	118	---	---	---	---	---	---	---	---
P-TM w/ Thermocouple & Heater Tape (No Groove)	758	164	---	---	---	---	---	---	---	---
P-TM w/ Thermocouple in Groove & Heater Tape	819	16	---	---	---	---	---	---	---	---
P-TM w/ RH @ 10-11%	746	8			618	38	374	16		
P-TM w/ Cup @ 40°C	886	13	658	27	620	4	419	8	649	31
P-TM w/ Cup @ 50°C	876	10	625	14	620	27	426	10	733	33
P-TM w/ Cup @ 60°C	806	53	639	9	610	11	424	8	730	18

P-TM: BOTD Proposed ASTM Test Method (Sept 2000)
*Recalculated from FY03 results to include disks with no wear scar (previously unconsidered data)